EUROfusion

Experiments on alpha particles with bump-on-tail distribution in JET DT plasmas (M21-08)

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Reference Session Leader: David Keeling
Task Force Leader: Jeronimo Garcia

JET

This work has been carried out within the framework of the EUROfusion Consortium and has received funding from the Euratom research and training programme 2014-2018 under grant agreement No 633053. The views and opinions expressed herein do not necessarily reflect those of the European Commission.

The Scientific Team:

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OUTLINE OF THE TALK

- **Why bump-on-tail? The background.**
- **Aim of the experiment.**
- **Description of the pulses and some transport analyses results.**
- **High frequency modes excited.**
- **Modelling of the modes observed (current status).**
- **Direct measurements of DT alpha-particles.**
- **Summary.**

WHY BUMP-ON-TAIL?

Background

The unexpected "pop-up" issue: Alfvén eigenmodes (AEs) in the elliptical gap in the Alfvén continuum, ~450-520 kHz, were excited in JET with D-He3 mixture (up to 27% of He3). These discharges had a rather short period sawteeth, and **among EAEs excited were modes with *n*=0 and *n*=-1 likely excited by α-particles born in D-He^3 fusion.**

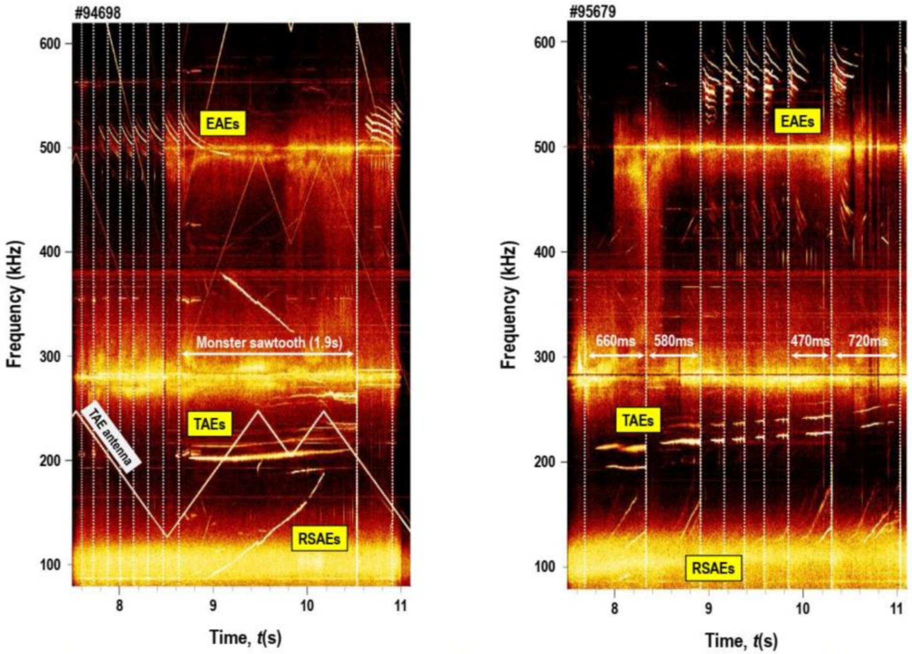
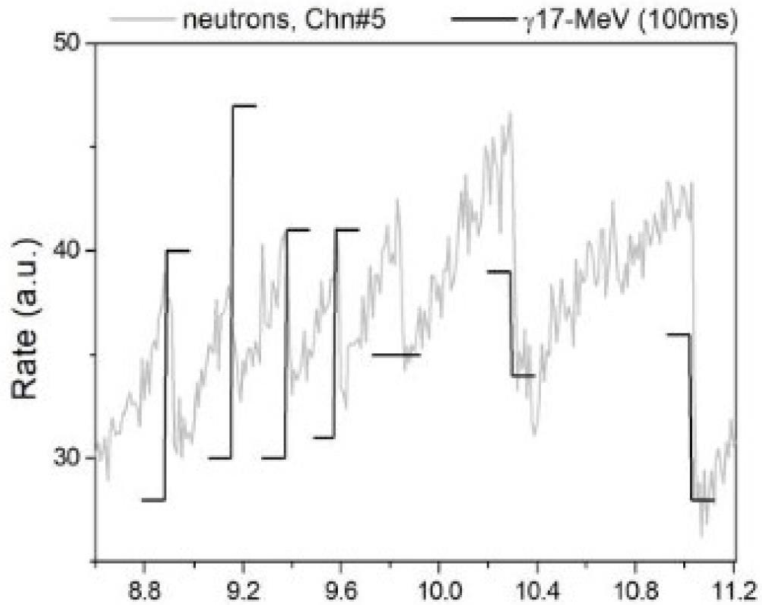


Figure 5. A rich variety of fast-on driven Alfvén eigenmodes is observed in D-^{3}He plasmas using the 3-ion D-(D$_{NBI}$)-^{3}He scenario: (a) #94698 and (b) #95679.

For details see *V G Kiptily et al 2022 Plasma Phys. Control. Fusion 64 064001*.

α-particle source measured with γ-diagnostic in D-He^3 plasmas

- Measured γ-rays born in α-particle collisions with Be impurities showed a significant **modulation of α-particle source** after every sawtooth.
- The **sawteeth have periods less than α-particle slowing-down time**. FP modelling showed that **under such conditions, a BOT distribution could be sustained for α's**.



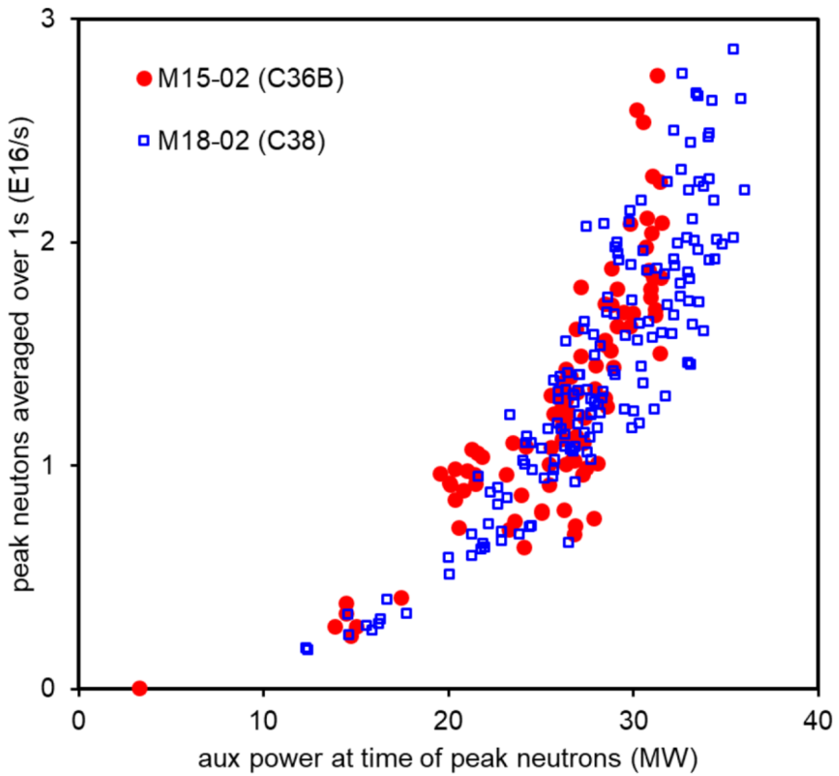
The sawtooth modulates alpha-particle source as follows (first 4 events):

$[P_\alpha(max) - P_\alpha(min)] / P_\alpha(max) \approx 30\%; 36\%; 27\%; 24\%$, so the average is ≈ 30%

Could we do NBI modulation, instead of short period sawteeth, for a sustained bump-on-tail distribution of α-particles in DT plasma?

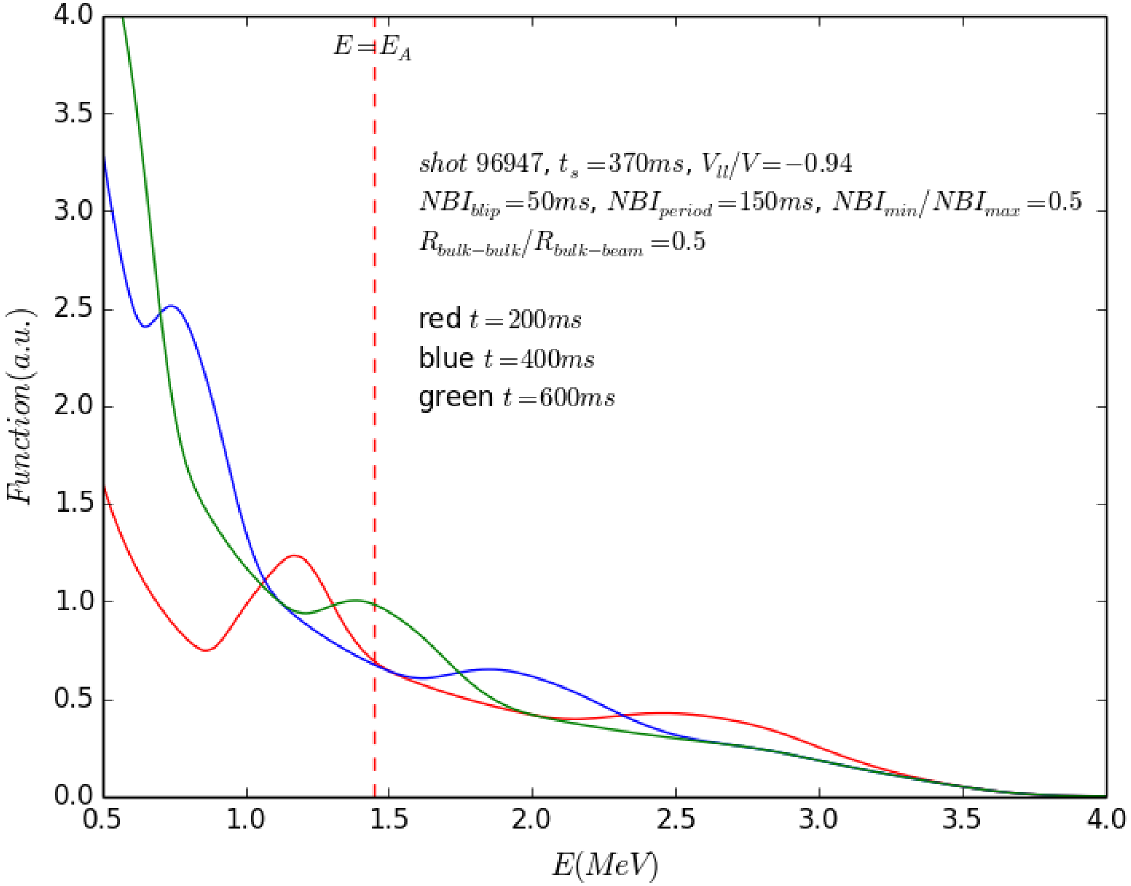
- **Pick up the scenario with dominant beam-plasma DT fusion;**
- **The Reference discharge had sawtooth period τ_{saw} ~250 ms;**
- **Alpha-particle slowing-down time was τ_{SD} ~370 ms;**
- **NBI modulation with periodicity similar to sawtooth should be OK for DT too as τ_{SD} is due to electrons (no difference what ion mix is for similar n_e, T_e);**
- **The depth of the NBI modulation should provide ~30% modulation in the α-particle source (similar to the sawtooth case in D-He^3 plasmas).**

Fusion yield in JET discharges with dominant beam-plasma contribution



- **At high power, ~30% of fusion yield requires ONLY ~15% of P_{in} modulation;**
- **However, DT neutron budget allowed us to do only P_{NBI}~ 10-15 MW.**

Modelling of bump-on-tail α-particle distribution via NBI modulation (1D FIDIT code by V.Goloborod'ko)



Scientific Rationale

In contrast to the scenario with elevated *q*-profile, where AE drive is amplified via the q^2 factor, the new scenario relies on alpha-particle bump-on-tail distribution. The *q*-profile could be close to unity → **hybrid and baseline scenarios could be explored**.

AE growth rate has contributions from the gradients of energetic particles in both radial and energy space:

$$\gamma_L \propto \int d^3\boldsymbol{r} \int dP_\phi dE(-e_\alpha \boldsymbol{V_d} \delta\boldsymbol{E})\delta(\Omega)\left(\omega\frac{\partial}{\partial E} + n\frac{\partial}{\partial P_\phi}\right) f_\alpha(E, P_\phi, \mu),$$

where the resonance condition between the wave with frequency ω and toroidal mode number n and the energetic particles has the following form:

$$\Omega \equiv (\dot{\Psi}_m) = n\dot{\phi} - (m+l)\dot{\vartheta} - \omega = n\omega_\phi(E,\ \ P_\phi,\ \ \mu) - p\omega_\vartheta(E,\ \ P_\phi,\ \ \mu) - \omega = 0,$$

~~

This gives the following normalized growth rate:

$\frac{\gamma_\alpha}{\omega} \cong -Cq^2\beta'_\alpha$ ← The scenario for q ~ 2 and not too high β'_α

$*\left(1 + \omega\frac{\partial f_\alpha}{\partial E} / n\frac{\partial f_\alpha}{\partial P_\phi}\right)$ ← **Bump-on-tail amplification if** $\frac{\partial f_\alpha}{\partial E} > 0$**.**

AIM OF THE DT EXPERIMENT

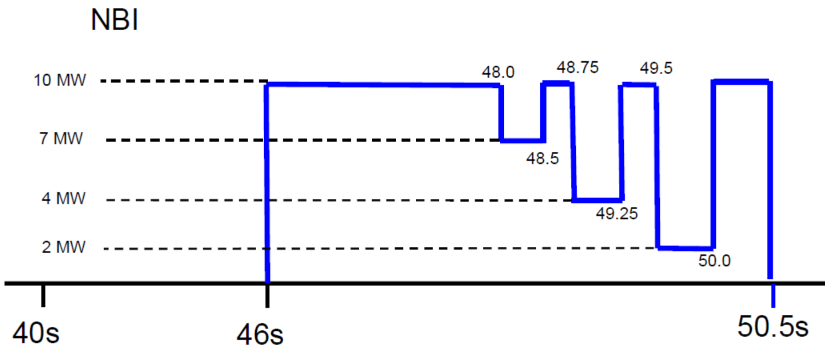
AIM OF THE EXPERIMENT:

- **Creating a bump-on-tail (BOT, $dF_\alpha/dE > 0$) α-particle distribution in JET DT pulses. Investigate alpha-particle excitation of Alfven Eigenmodes (AEs). Compare to previously seen D-He^3 plasmas with alpha-particle driven AEs.**

- **In contrast to the beam afterglow scenario with elevated q-profile, the BOT scenario uses q(0) close to unity.**

- **The critical question this experiment could answer is: whether we could, e.g., via modulating NBI power, create a BOT distribution of α-particles, which shifts notably the AE instability zones in burning plasmas.**

NBI only discharges were employed with the power modulation:



THE PULSE BRIEF SUMMARY:

Pre-DT:

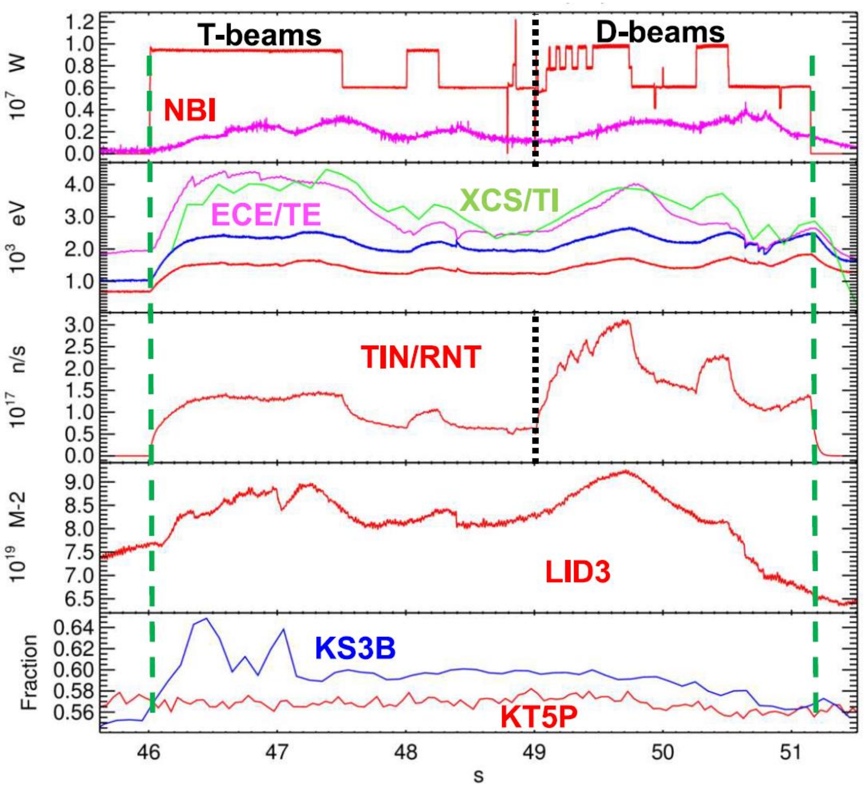
- **There was no direct reference pulse in D-only plasmas.**
- **The pulse types have been adapted from the pulse #95679 that showed the desired characteristics and which has been modified appropriately.**

DT pulses:

- **##99500-99503 plus contingency pulse #99627 (5 pulses).**
- **B_T = 3.7 T, I_P = 2.5 MA.**
- **NBI only so no fast ions in the MeV range apart from alpha-particles.**
- **Both D and T beams used, power up to P_{NBI} = 10 – 15 MW.**
- **Tritium concentration was varied from D:T = 33:67 (T-rich plasmas) to D:T = 55:45 (D-rich plasmas).**

DESCRIPTION OF THE PULSES AND SOME ANALYSES WITH 1D FP MODEL AND TRANSP

#99500 T BEAM, THEN D BEAM INJECTED INTO DT PLASMA:

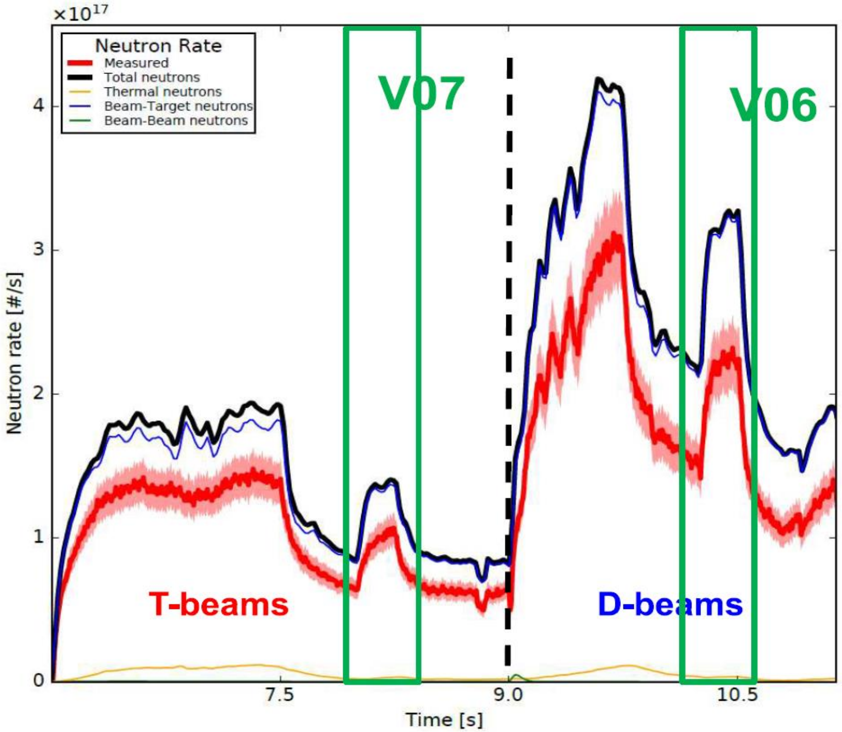


Top to bottom: **NBI and Radiation power; T_e from ECE and T_i from CX; neutron yield; density $\int n_e(L)dL$ through the magnetic axis line-of-sight; T fraction.**

TRANSP ANALYSIS OVERESTIMATES NEUTRON YIELD IN BOTH D-BEAM AND T-BEAM CASES IN OUR DISCHARGES:

Neutrons:

KN1 fission chambers



Fast ion output (300k ptcls)

99500V06: D-beam ion and alpha tracking, 50 ms output width, EOI: [10.25,10.30,10.35,10.40,10.45,10.50,10.55,10.60,10.65] s

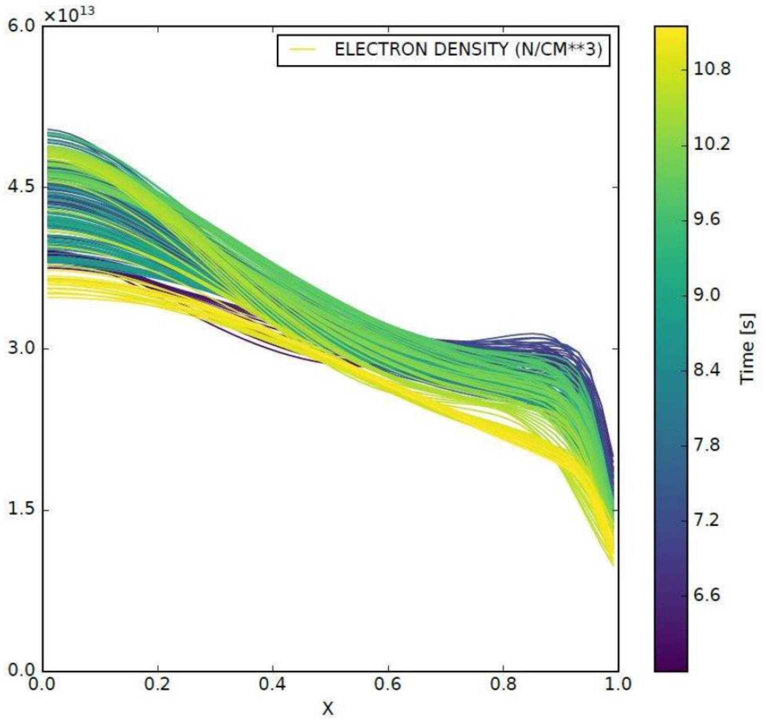
99500V07: T-beam ion and alpha tracking, 50 ms output width, EOI: [8.00,8.05,8.10,8.15,8.20,8.25,8.30,8.35,8,40] s

Z.Stancar

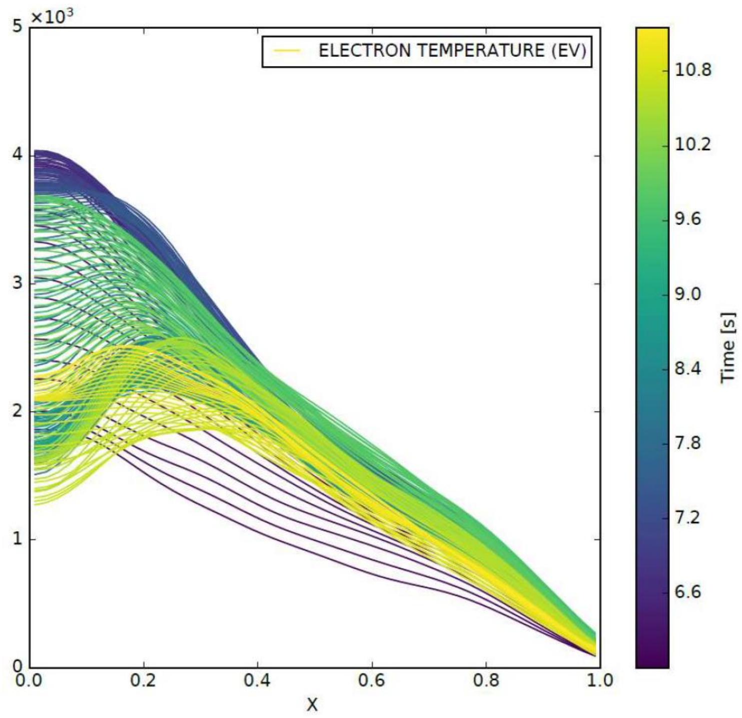
Input profiles

99500V02

NE

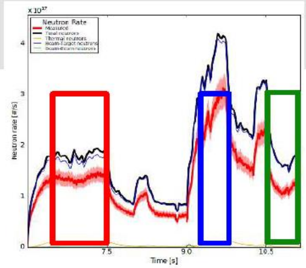


TE



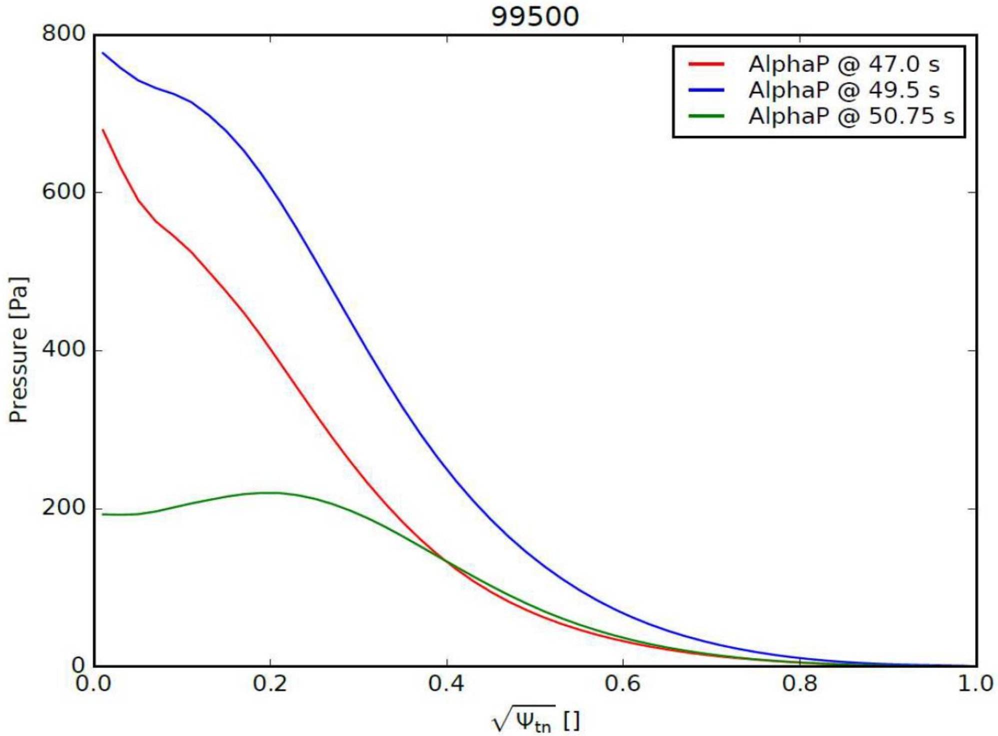
Alpha results

99500V02



Alpha pressure

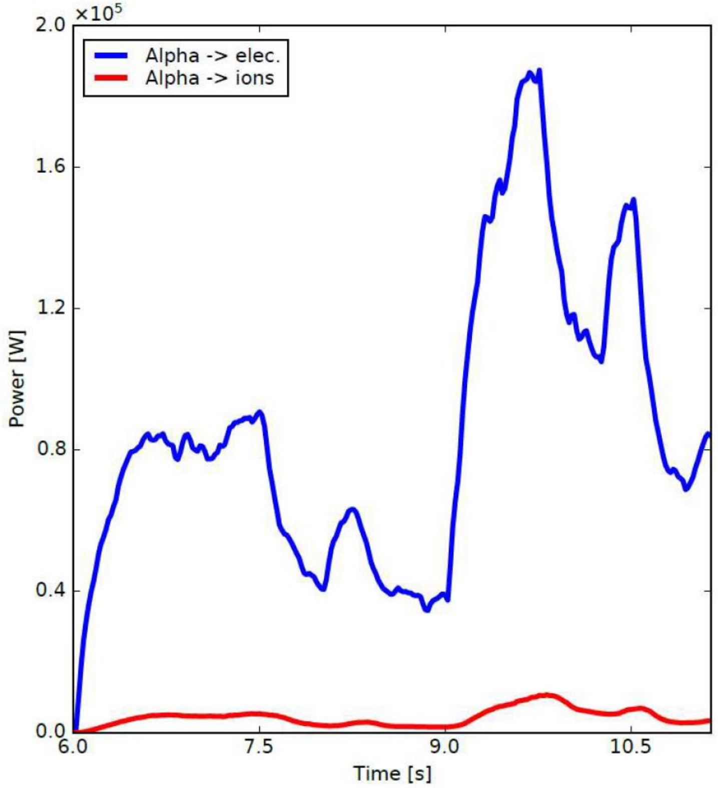
α contribution ~ several % to core pressure



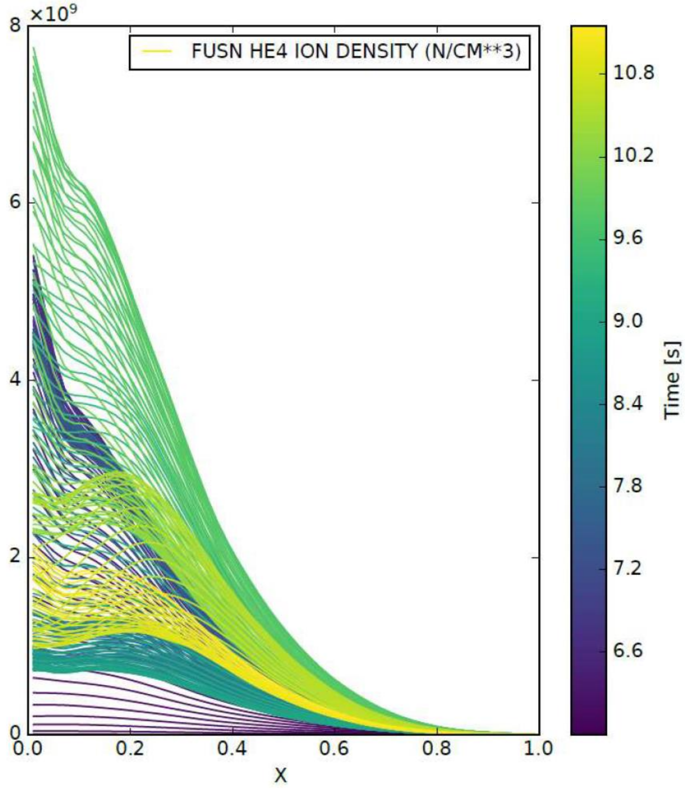
Alpha results

99500V02

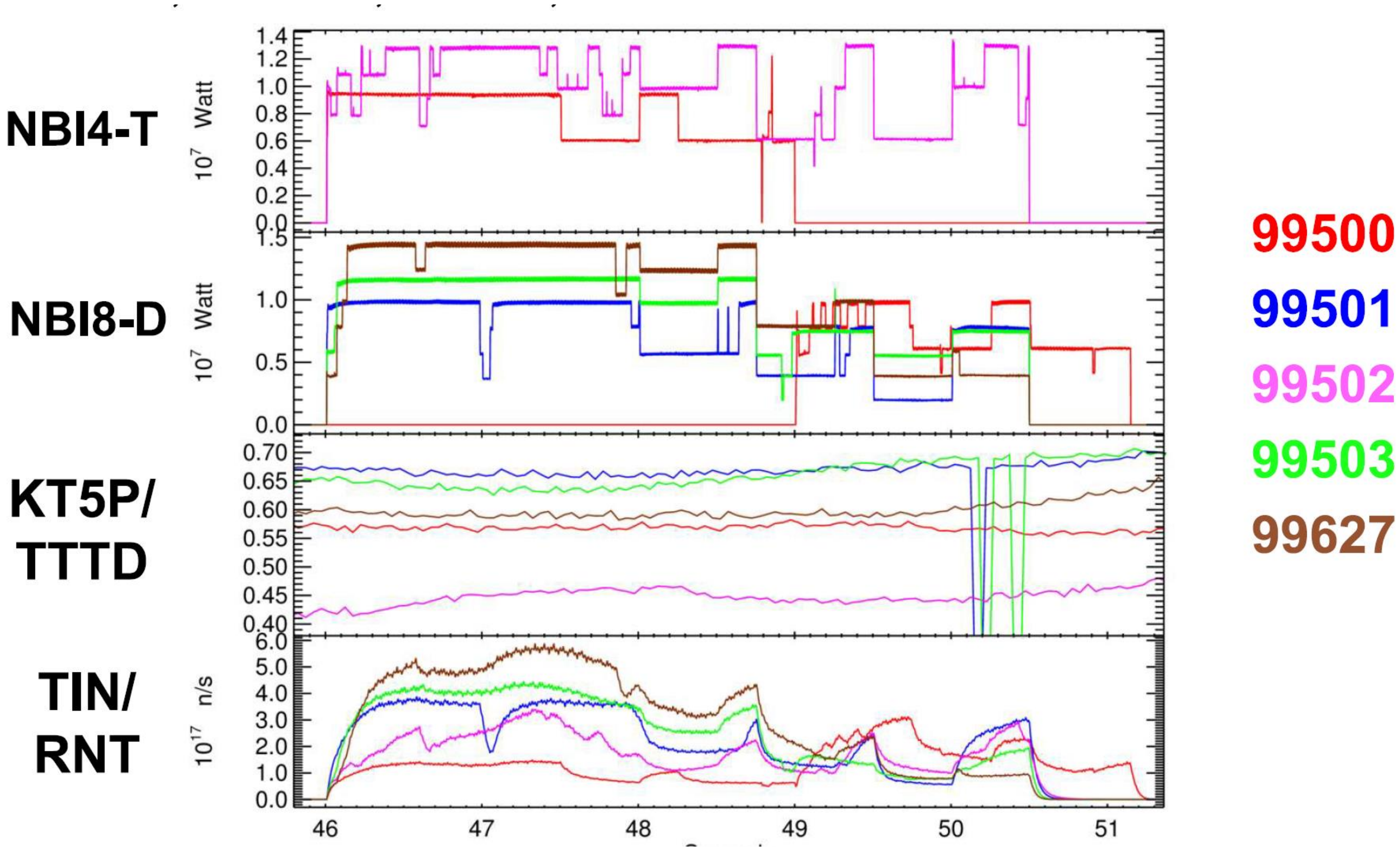
Alpha heating



Alpha density

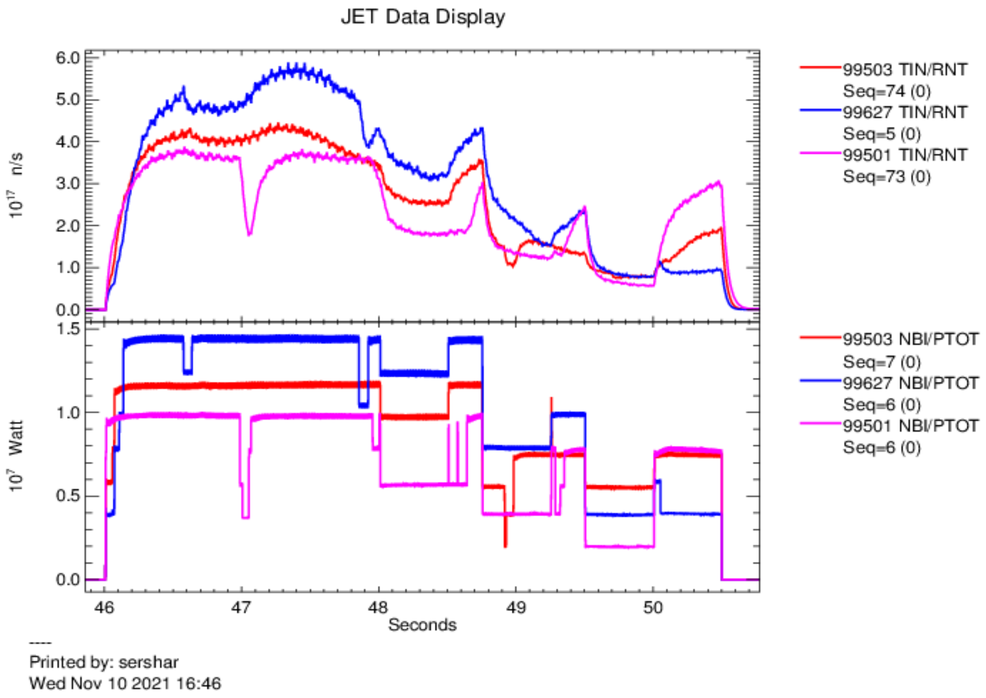


COMPARISON OF T-NBI, D-NBI, AND D:T IN ALL PULSES



Did we achieve bump-on-tail distribution in alpha-particles?

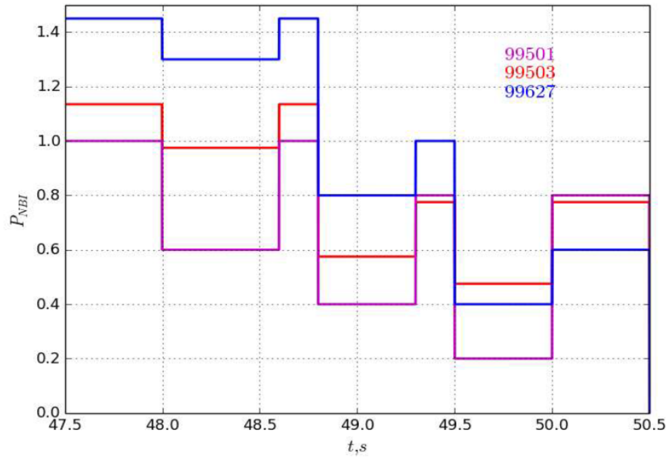
Compare 3 pulses with modulated D-beam of increasing P_{NBI} into T-rich plasma:



Top to bottom:

Neutron rate (x10^{17} n/s); NBI power (MW);

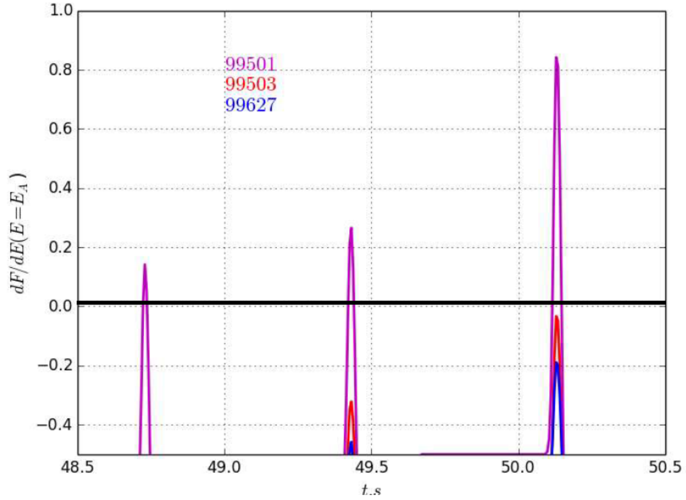
1D simulation of alpha distribution function evolution



← Modelled evolution of D NBI power

$$\frac{\partial F}{\partial t} + \frac{1}{v^2}\frac{\partial}{\partial v}\tau_s^{-1}\left(v^3 + v_c^3\right)F = S\left(v, \frac{v_\parallel}{v}, t\right)$$

$$S\left(v, \frac{v_\parallel}{v}, t\right) = S_{target-target}\left(v\right) + S_{beam-target}\left(v, \frac{v_\parallel}{v}, t\right)$$

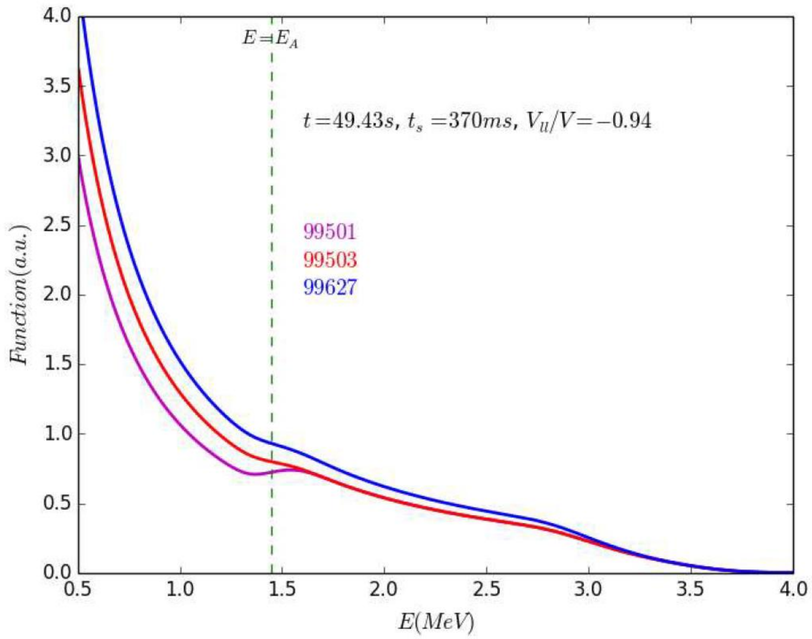


E_A=1.45MeV, τ_s=0.37s, $V_{||}/V$=-0.94

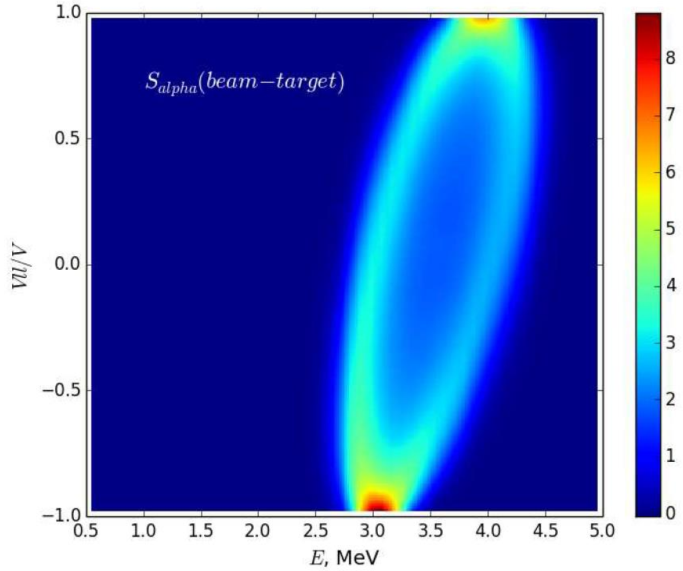
- Only in #99501 positive derivative dF/dE at E=E_A may be expected
- Bump-on-tail in #99503 and #99627 exists for high energies but not for E=E_A

V. Goloborodko

1D simulation of alpha distribution function



Example of fusion alphas distribution function

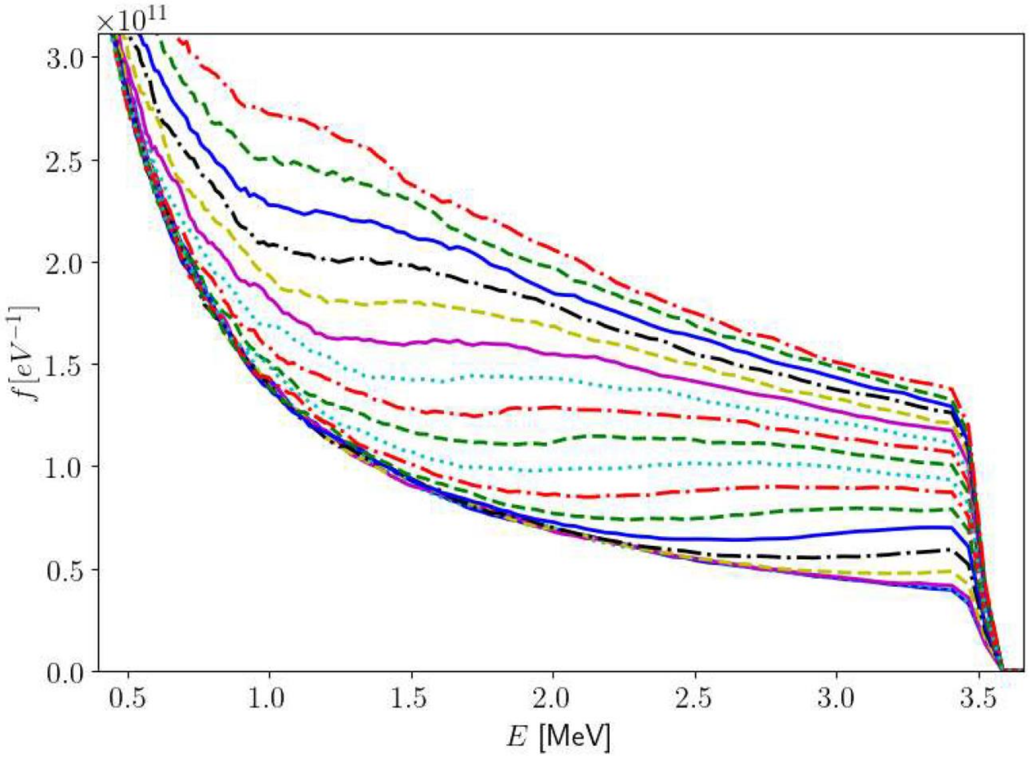


Beam-target fusion alpha source used in simulations (in addition to target-target contribution)

For a glance, the main role for the formation bump-on-tail distribution of fusion alphas at $E=E_A$ play the beam power modulation, razer then beam power itself

CONFIRMED BY TRANSP ANALYSIS OF BUMP-ON-TAIL IN ALPHAS (FINE TIME STEPS AND HIGH STATISTICS USED):

99501 V08+V09: 5ms windows from 50.00 to 50.09



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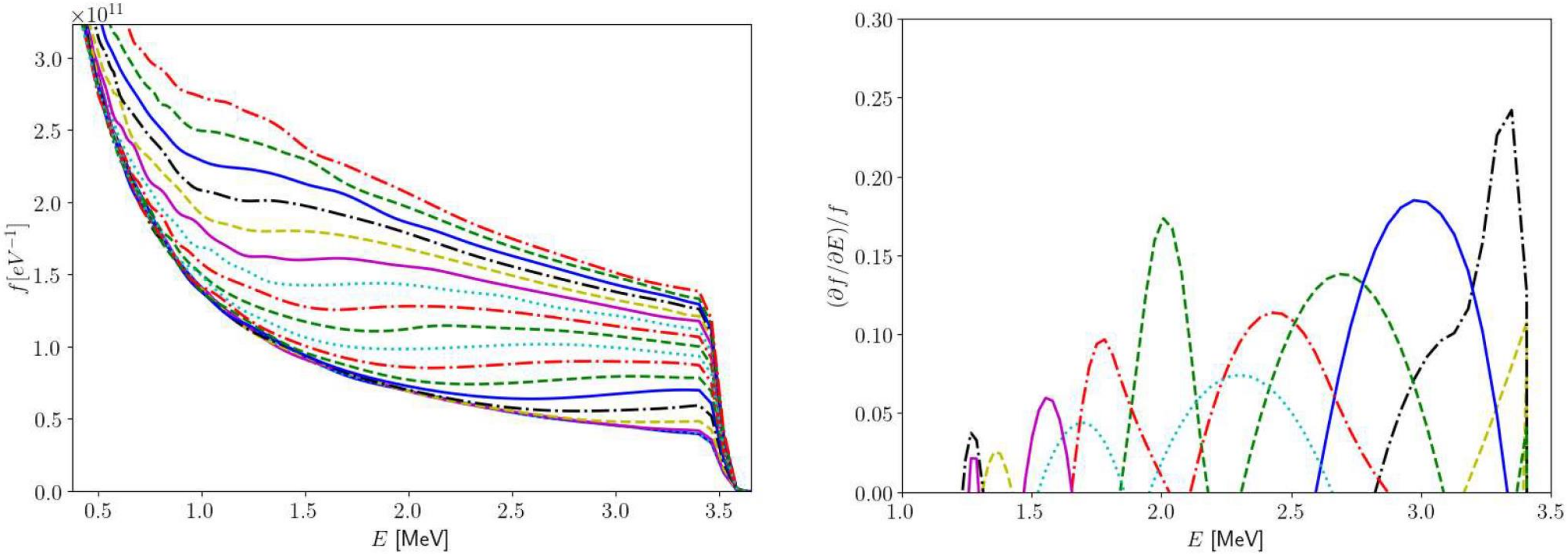
TRANSP ANALYSIS OF BUMP-ON-TAIL IN ALPHAS (cont'd):

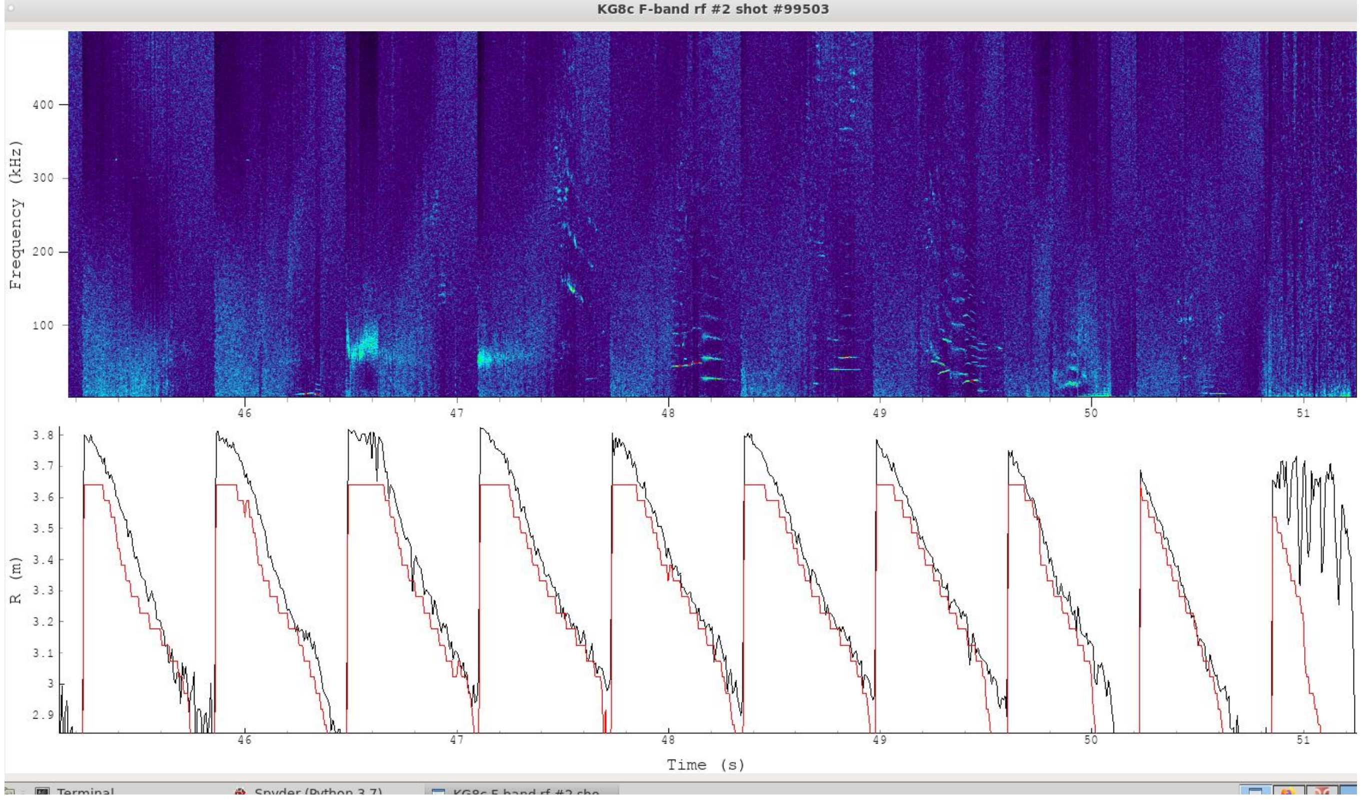
Positive gradients present at wide range of energies



HIGH FREQUENCY MODES OBSERVED IN ALL DISCHARGES

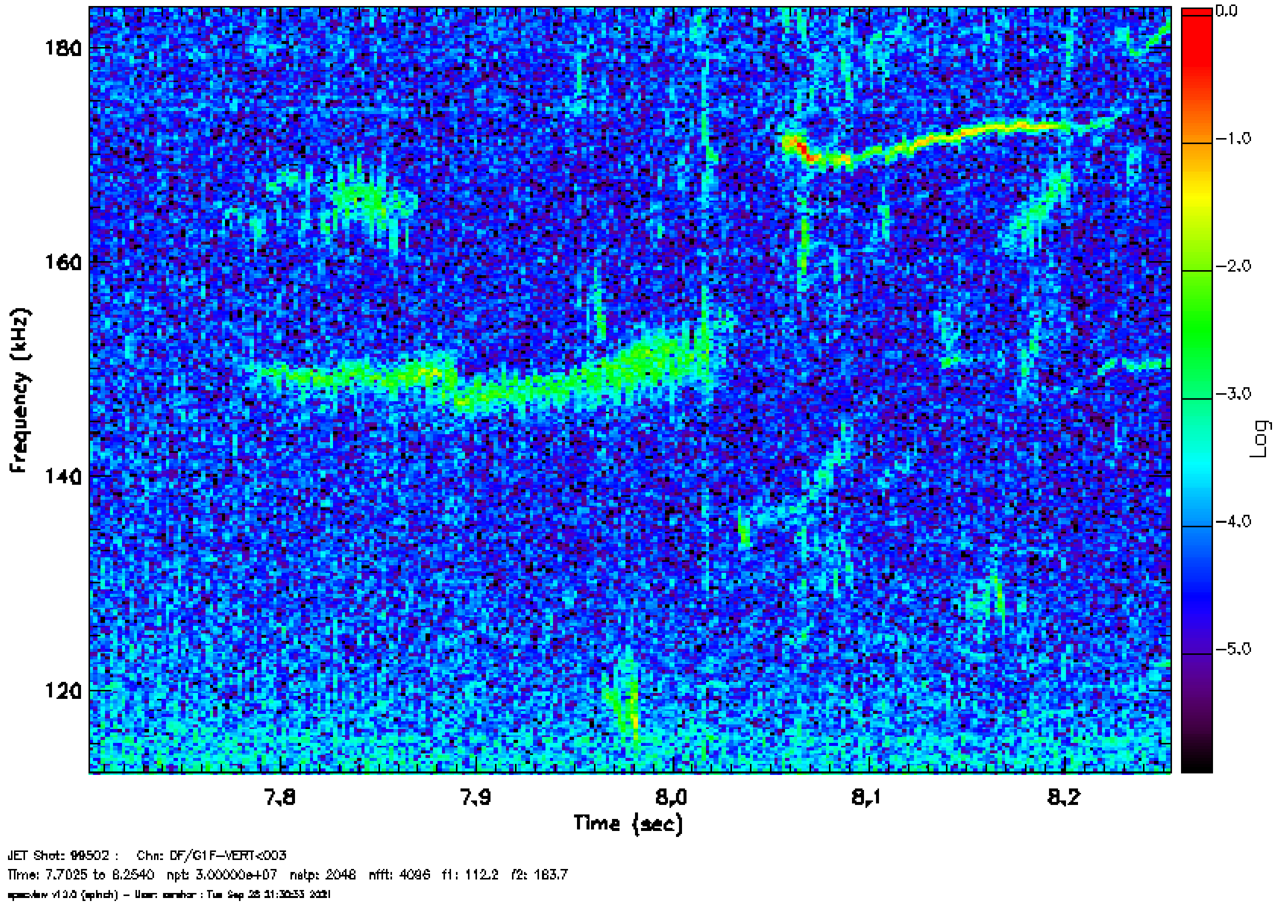
Modes up to 500 kHz seen in reflectometry, interferometry, SXR. Not seen by Mirnov coils above ~75 kHz.

Reflectometry shows the mode localisation at <r/a ~0.3:



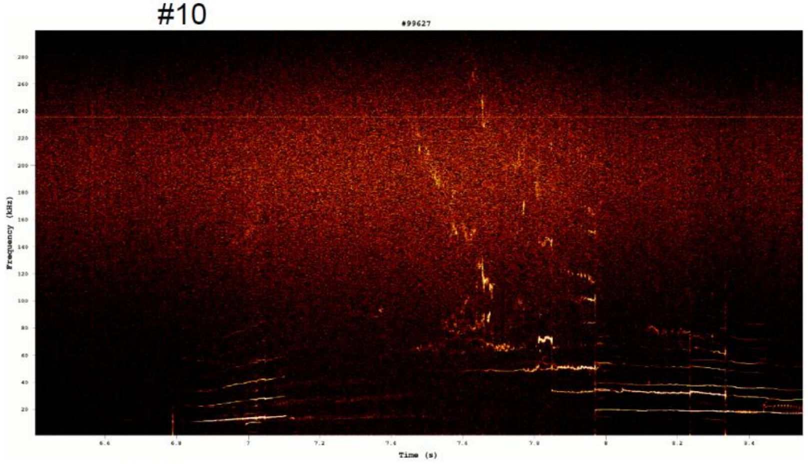
M.Dreval & C.Giroud

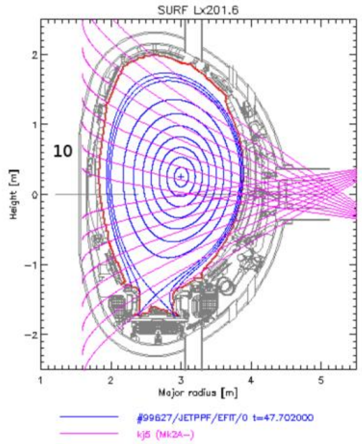
Interferometry KG1F/LID3 (frequency$_{KG1F}$ = f + 100 kHz)



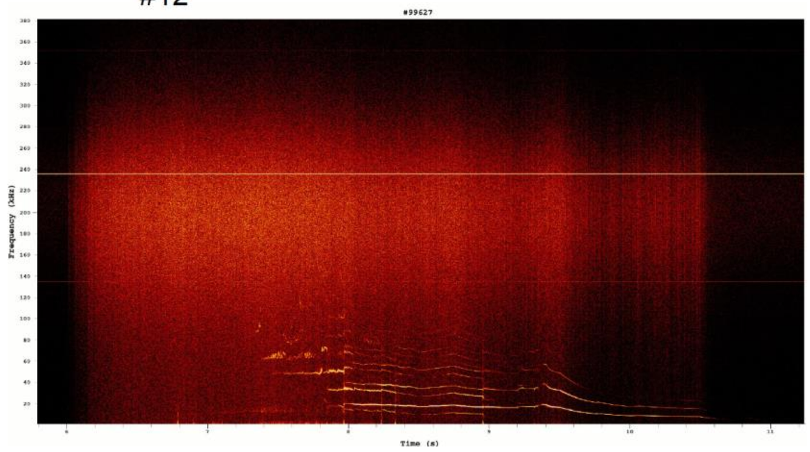
High frequency modes are also seen in SXR. These are very HIGHLY LOCALIZED!

#10





#12



7.4-8s modes >100kHz
are core localized

MODELLING OF THE MODES OBSERVED

Selected time-slices

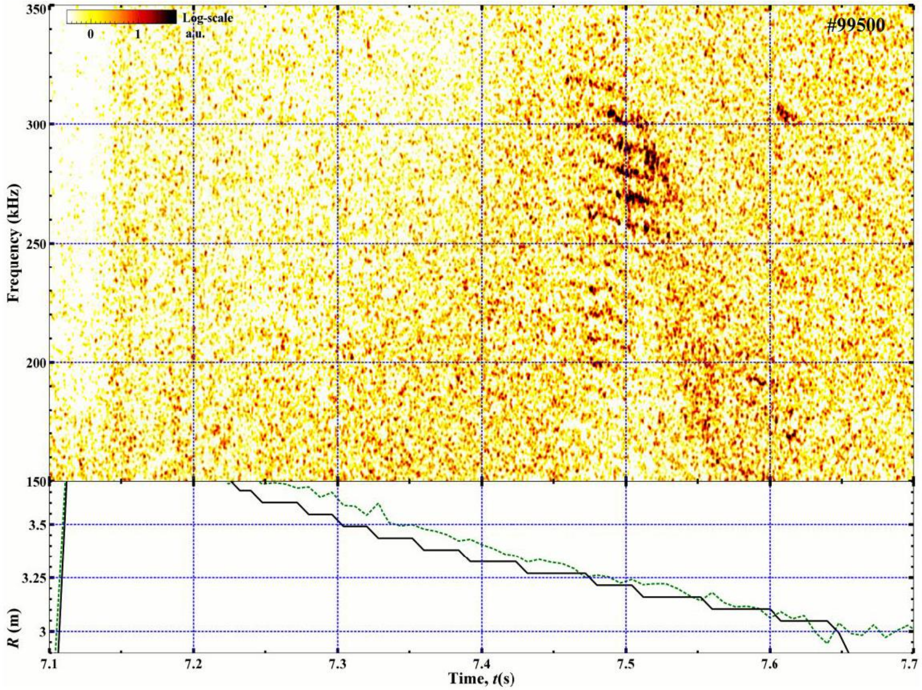
- Picked timeslices with high frequency modes but no activity at low frequency:
  - 99500 t=47.5s
  - 99502 t=47.5s
  - 99503 t=47.5s

- Validated q profile with MHD markers, used the latest TRANSP runs for polynomial fit of density profile.

- Run HELENA, CSCAS, and MISHKA for each case, scanning over frequency and toroidal mode number.
  - ~ 1k MISHKA runs to find ~100 modes for each gap and timeslice.

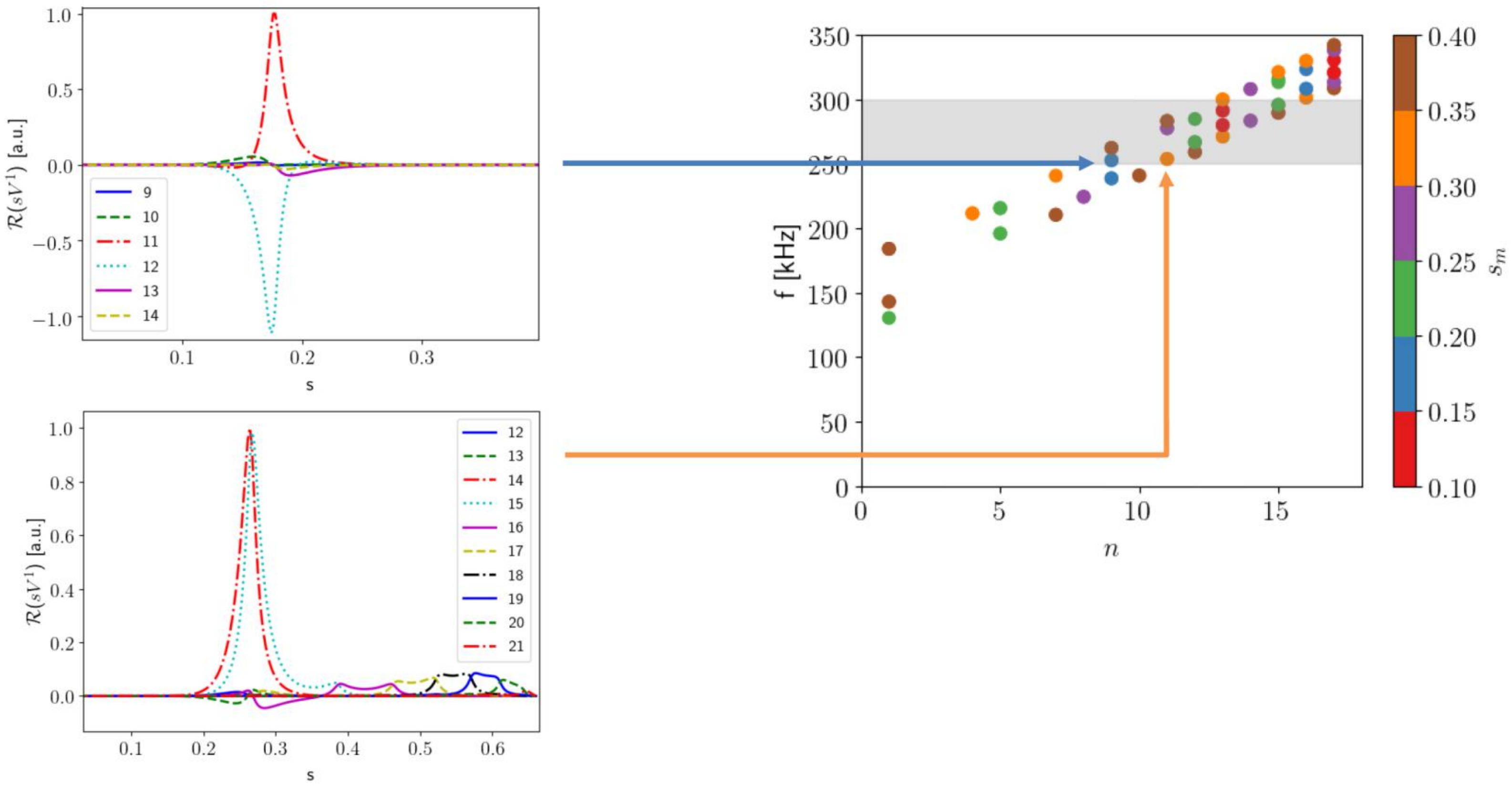
J.Oliver et al.

MODES SEEN WITH REFLECTOMETRY IN #99500:

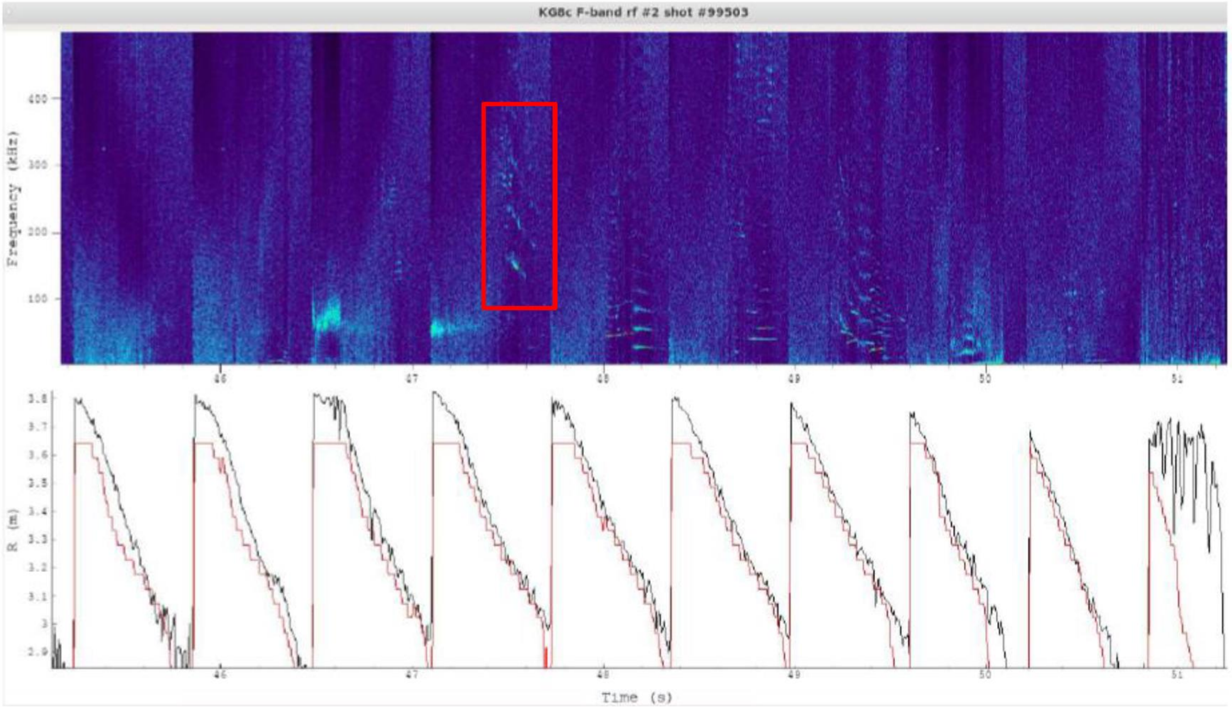


TAEs WITH 9 ≤ n ≤ 16 FOUND WITH MISHKA CODE IN THE RIGHT LOCATION AND FREQUENCY RANGE

99500 t=47.5s: odd and even TAEs found



99503 t=47.5s: two groups of modes observed



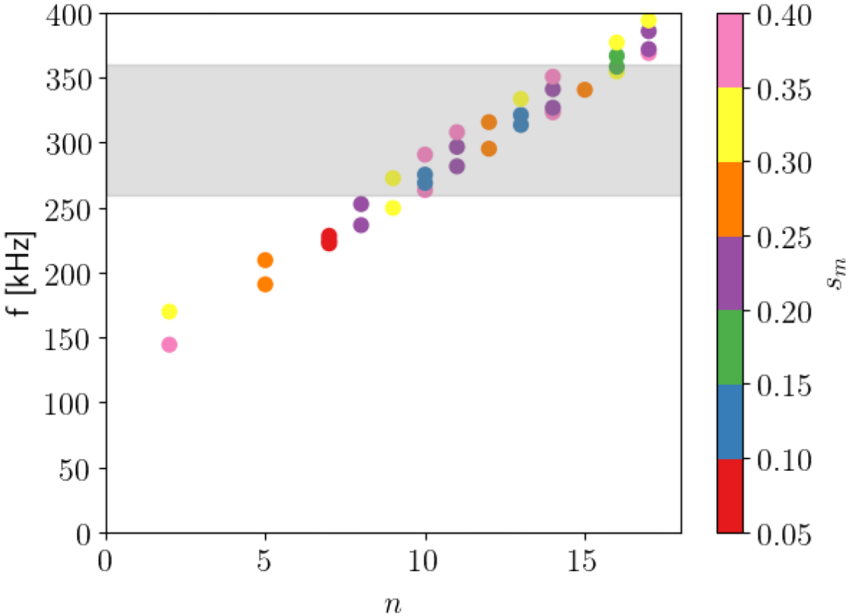
Modes with large frequency separation:

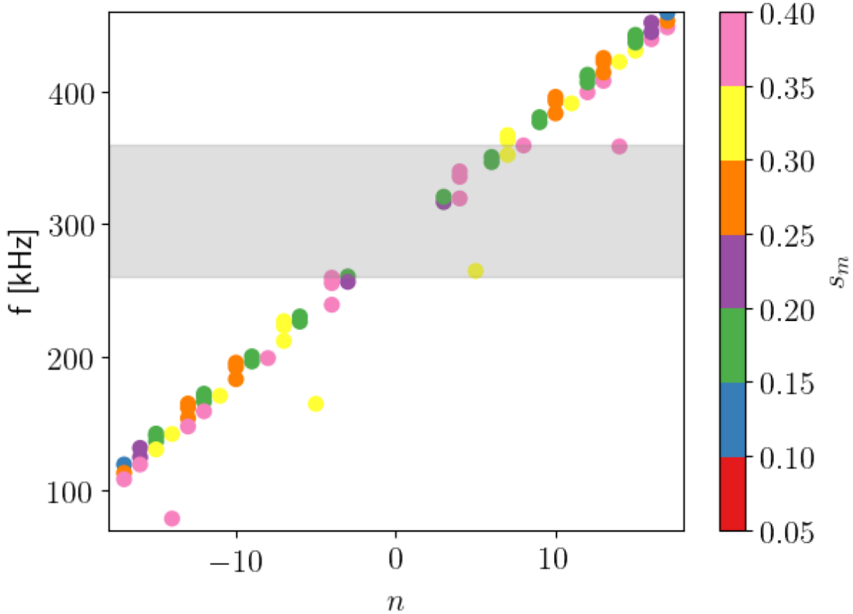
- $140 - 170 kHz$ and $3.1 \le R[m] \le 3.25$
- $200 - 240 kHz$ and $3.1 \le R[m] \le 3.25$
- $260 - 300 kHz$ and $R \sim 3.25\, m$

Modes with smaller frequency separation:

- $R \sim 3.25\, m$
- $260 \le f[kHz] \le 360$

99503 t=47.5s: TAEs match observed modes





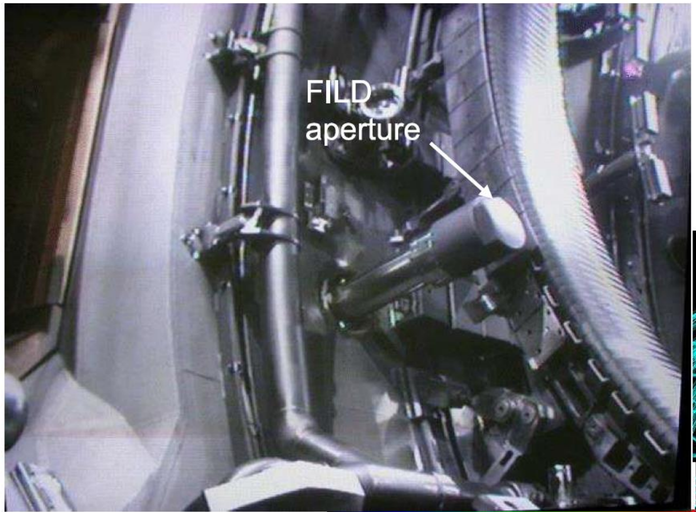
TAEs with $9 \leq n \leq 16$ are found in the right location and frequency range.

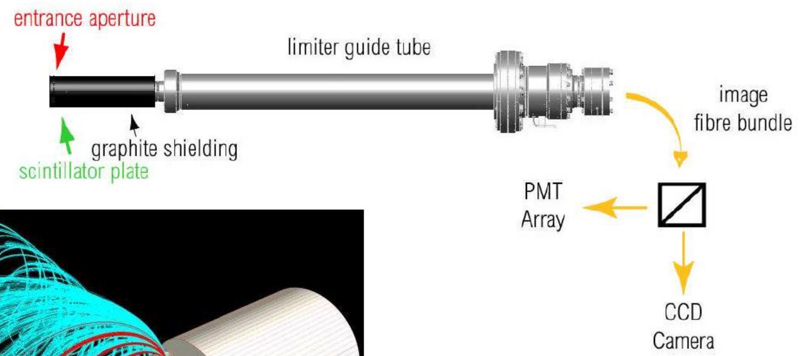
EAEs don't match the observed modes, there is no EAE gap in the core for low n.

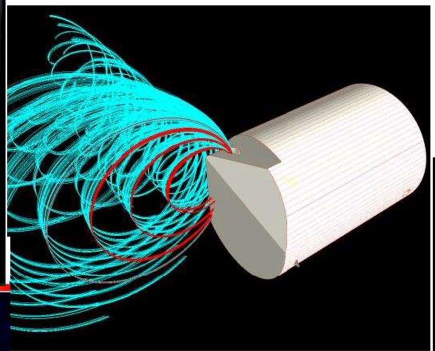
DIRECT MEASUREMENTS OF DT ALPHAS

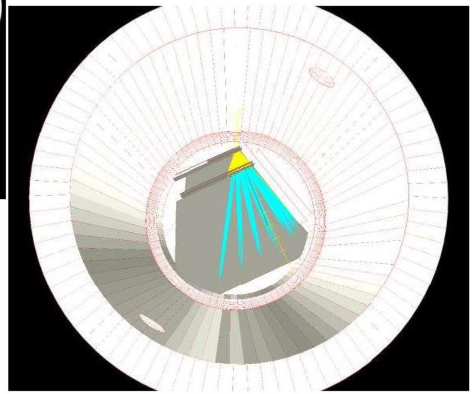
Fast Ion Loss Detector

Scintillator Probe – KA3

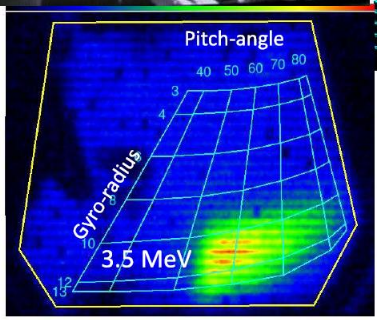








DT fusion
alpha-particles
prompt losses!

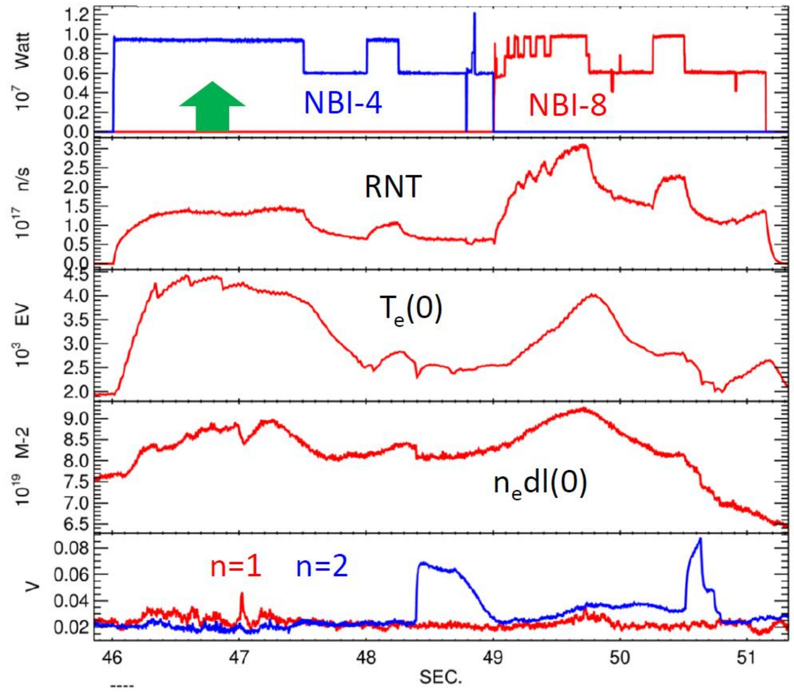


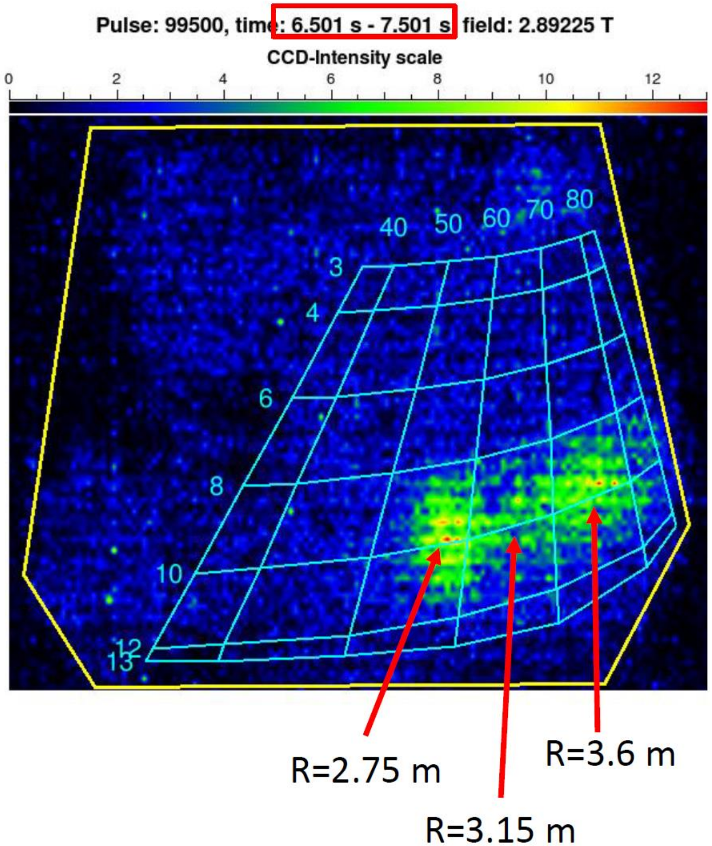
- Modelling of lost ions orbits
- Lost ions image on scintillator plate

Darrow D. et al. Rev. Sci. Instrum. **77** (2006) 10E701
Kiptily V.G. et al Nucl. Fusion **49** (2009) 065030

#99500: T- & D-NBI

3.7T / 2.5 MA, ~58% tritium

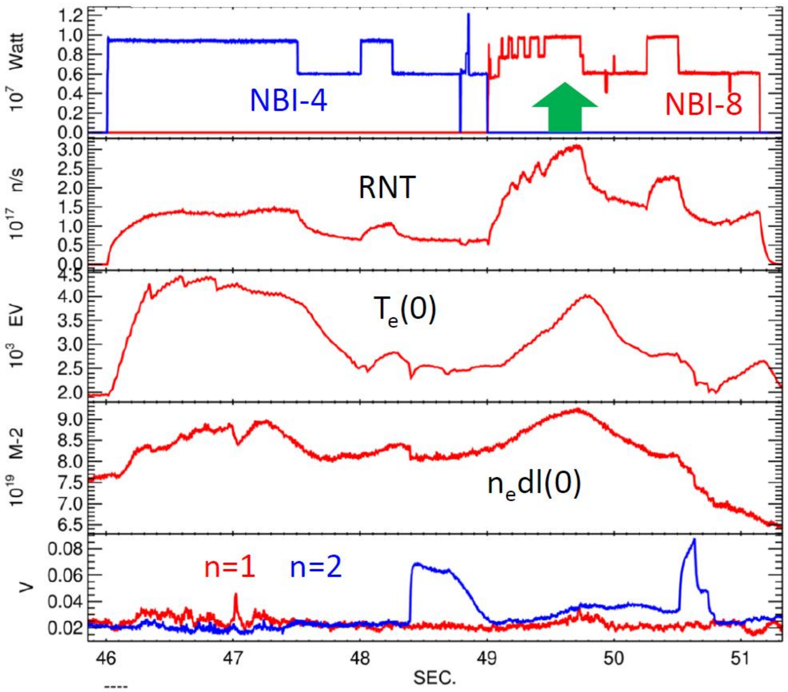


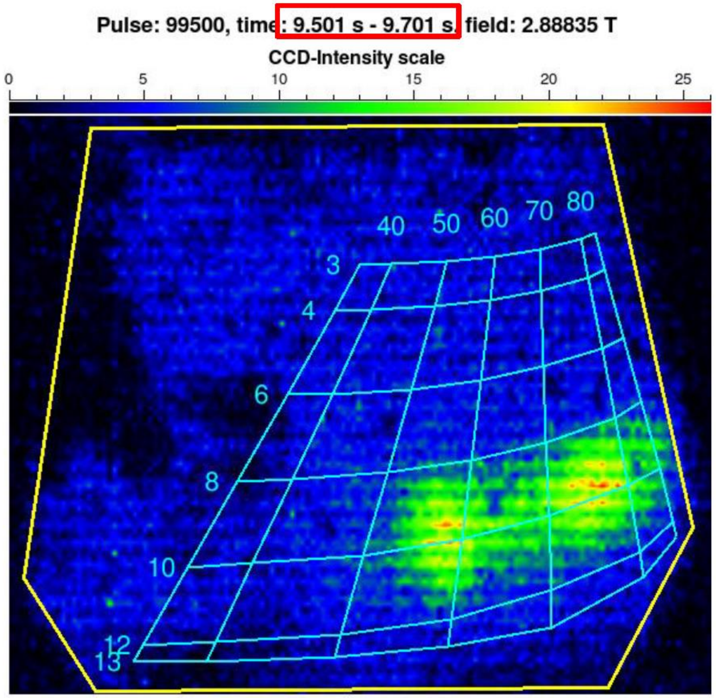


V.G.Kiptily

#99500: T- & D-NBI

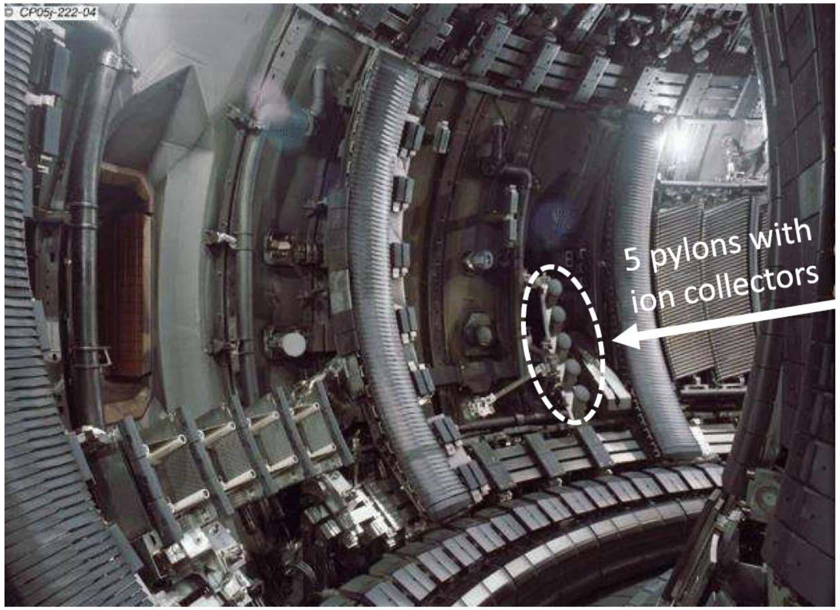
3.7T / 2.5 MA, ~58% tritium

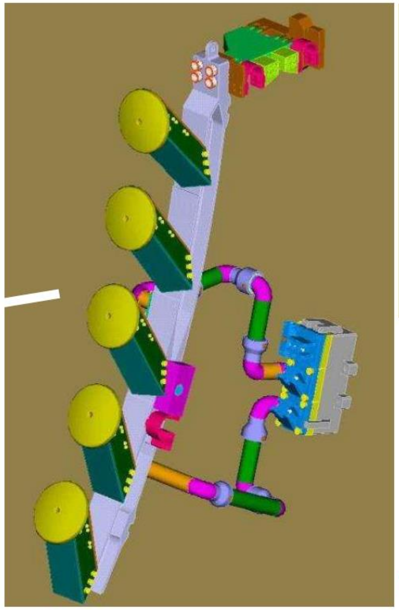


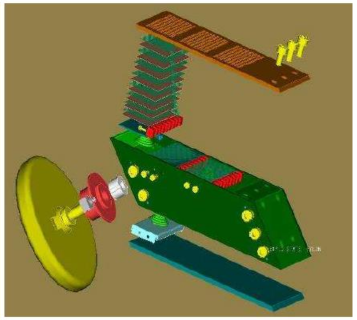


Faraday Cups: α-particle losses

Faraday Cups







- Perforated cover to admit ions
- Stack of alternating Ni foils and mica insulating sheets
- Ion current measured for each foil individually
- Ion energy determines deposition depth

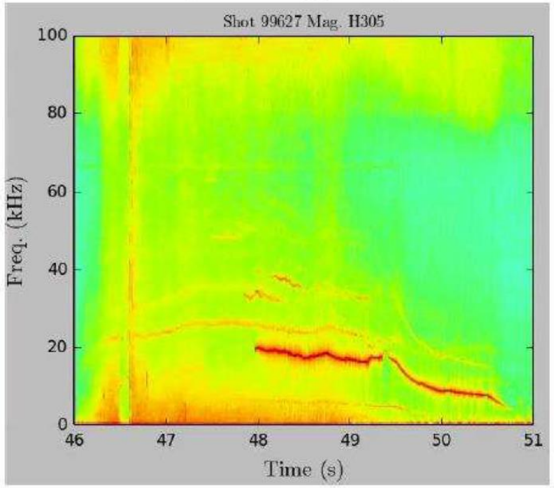
Faraday Cups array was designed for lost α–particle measurements in DT-plasmas

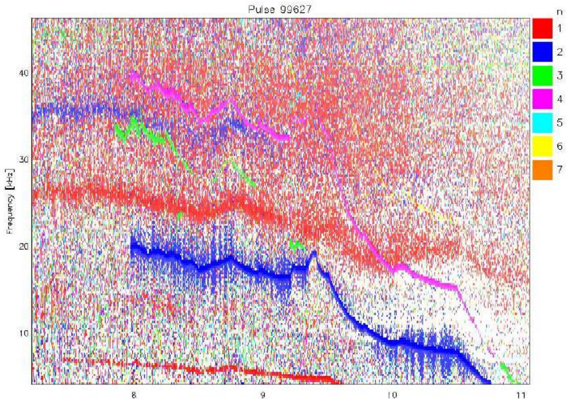
Darrow D. S. et al Rev. Sci. Instrum. **75** (2004) 3566
Kiptily V.G. et al Nucl. Fusion **49** (2009) 065030

Faraday Cups and MHD modes

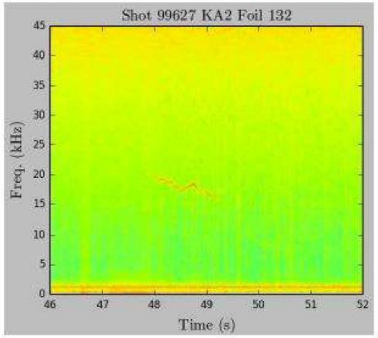
#99627: D-NBI

H305 Magnetics





Foil 132 Minus Rear Foil



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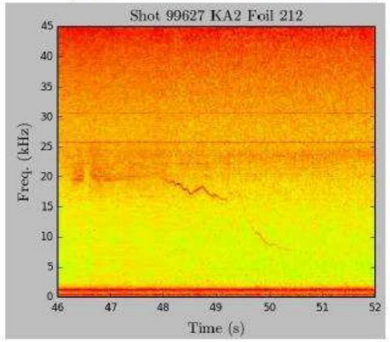

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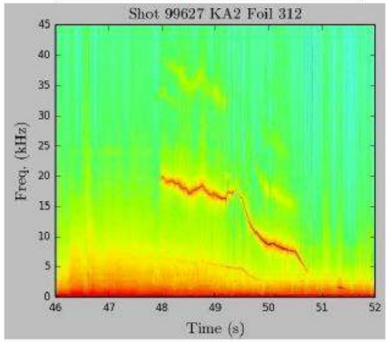
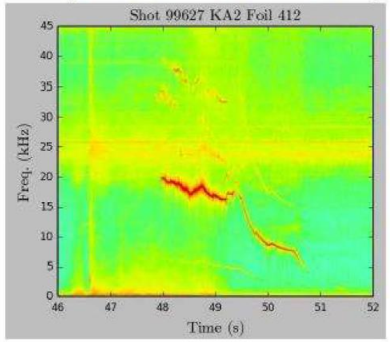


Foil 412 Minus Rear Foil



SUMMARY ON THE DELIVERABLES:

D1 Achieve modulation of alpha-particle source with NBI power sufficient for sustaining bump-on-tail in alpha-particle distribution (Done);

D2 Demonstrate AE excitation by alphas in NBI heated plasmas with q~ 1 (Done);

D3 Provided that M21-05 demonstrate efficient ion heating with low energy fast ions, apply 3 ions scheme together with NBI modulation; - Irrelevant

D4 Assess the possibility of bump-on-tail and make predictions on alpha-driven and NNBI-driven AEs for ITER, which may be of primary interest for sawtoothing discharges on the path to the operational Q=10 point. (To be done)

ANALYSES AND ONGOING MODELLING:

- **TRANSP done for all DT pulses;**
- **Bump-on-tail analysis partly done with the 1D model and TRANSP;**
- **MISHKA modelling of AEs fitting the observed modes partly done;**
- **Kinetic drive and damping analysis to be performed next.**